Groundwater Storage Analysis Using Deterministic Model Approach for Water Resources Management of Zamfara part of Sokoto-Rima Basin, Nigeria

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ABSTRACT

The study area is entirely located within the Sokoto-Rima hydrological basin of Northwest, Nigeria. Groundwater is widely used for drinking, domestic and agricultural purposes in Zamfara water catchment. The mismanagement of groundwater resources could cause negative effects including depletion of aquifer storage and groundwater level decline. To assure sustainability of the available resources, determination of groundwater budget is necessary. Deterministic model approach was used, which required three quantities (Available water quantity, Abstractible and Storable water volume). In this study meteorological water budget (MWB), water level fluctuation (WTF), and groundwater budget based on geological framework (GBBDF) were used to estimate water budget. Groundwater recharge and abstraction rate were calculated from 280 borehole data across the water catchment area. The average groundwater budget of the study area was calculated as 111,693,470 m^3/year with the MWB method and it was calculated as 111,342,057.3m^3/year and 73,463,099 m^3/year with the WTF and (GBBDF) methods respectively. The groundwater abstraction for domestic/agricultural uses was calculated to be higher to that of aquifer recharge. Thus prudent measure has to be adopted for adequate water use per head as population increase and demographic change will exacerbate more stress on the availability of this precious resources aside the climate change impact. The implication is that further proliferation of borehole wells will deplete the entire aquifer and subject it to be devoid of manageable storage capacity, particularly in the crystalline aquiferous units. It is clear that, if conceptual hydrogeological modelling of the catchment is well known and reliable data are obtained, the MWB method gives accurate results in the basins. However, comparison of multiple methods is valuable for determining the plausible budget amount and for highlighting the uncertainty of the estimate.

Keywords: Zamfara Hydrogeological Catchment, Groundwater budget, Aquifer Recharge/Abstraction, Sustainable Management

1.0. Introduction

Nowadays, the most important problem is decreasing of groundwater quantity due to unplanned usage. The sustainable management of these natural resources in semi-arid and arid areas requires a detailed understanding of the regional hydrological and hydrogeological processes. The groundwater balance of a catchment and the processes of recharge, storage, evapotranspiration loss and discharge can be described by simple but physically based conceptual model components (Aksever *et al.,* 2015). Correct determination of the groundwater budget in a basin is associated with the selection of suitable budget calculation methods as well as the associated understanding of the regional hydrological and hydrogeological processes in detail. It is difficult to estimate the water budget reliably by a single method because of uncertainties and assumptions associated with different methods (Garba and Schoeneik, 2005). For this reason, it is commonly recommended that the water budget should be estimated using multiple methods.

Groundwater is an important water resource both for the maintenance of the natural environment and for human needs. Groundwater can be regarded as a renewable natural resource if there is a balance between recharge and abstractions of the aquifer (Voudouris, 2006). Groundwater recharge and discharge are critical to understanding the hydrologic cycle and to managing water resources. Good groundwater resources management practices require developing a water budget approach on a regional or large scale for an entire aquifer or geographic region (Cherkauer, 2004). The sustainable management of the groundwater resources especially in basins depends on a detailed understanding of the regional hydrology and hydrogeological processes. In other words, understanding the groundwater reserve (potential and/or budget) is an essential prerequisite for managing the groundwater system sustainably. Therefore, a well-known conceptual hydrogeological model of the basin is of great importance. The model plays a very useful role in the recharge estimation process (Scanlon *et al.*, 2002) and in the groundwater resources management plan.

In addition, the correct determination of the groundwater budget in a basin is also associated with the selection of a suitable budget calculation method. Different techniques are used to calculate the groundwater recharge and discharge amount; however, choosing appropriate techniques are often difficult. Various factors need to be considered when choosing a method to quantify recharge. A thorough understanding of the attributes of the different techniques is critical (Scanlon *et al.*, 2002). The detailed studies of groundwater budget assessment in different basins were made by many researchers (Alamin, 1979; Kim *et al.*, 2001; Bredehoeft, 2002; Scanlon *et al.*, 2002; Welsh, 2002; Devlin and Sophocleous, 2004; Dunkeloh, 2005; Al Obied, 2007; Nilsson *et al.*, 2009; Elsheikh *et al.*, 2011). Lee *et al.* (1999) and Chen *et al.* (1999) estimated groundwater recharge by adopting the water-budget model, combining the rainfall data and soil parameters with the infiltration model. Finch (1998) used a simple water-balance model to study effects of land surface parameters on groundwater recharge. Lee *et al.* (2000) also applied the water-balance method in conjunction with an independent estimation of recharge from a finite-difference simulation of groundwater levels. Simmons and Meyer (2000) provided a simplified model for the transient water budget of a shallow unsaturated zone to estimate groundwater recharge. Dunkeloh (2005) applied the physical water balance model (MODBIL) for the determination of the water budget. The main water balance components such as precipitation, actual evapotranspiration, run-off and groundwater recharge are given out in this method. The model results provide an insight into the physical system, e.g., interactions of the regional, meteorological, hydrological, and hydrogeological processes, the intra and inter-annual variability, and the impacts on the regional water resources. According to Yin *et al.* (2011), groundwater recharge is a key factor in water balance studies, especially in (semi-) arid areas. For the estimation of groundwater recharge, they used multiple methods such as water-table fluctuation, Darcy's law and the water budget. Elsheikh *et al.* (2011) investigated the groundwater budget for the alluvial aquifer in Sudan. In this study, the input to the groundwater is mainly represented by the infiltration from surface water, direct infiltration and the underground inflow while the output includes evapotranspiration, pumping and underground outflow. Groundwater balance is determined with the annual input and output quantities. For the groundwater budget calculation, the choice of methods will depend on the spatial and temporal scale of investigation, characteristics of the aquifer, mechanism sought for understanding, availability of data of adequate quantity and quality, and spatial and temporal resolution of the results (Flint *et al.*, 2002; Heppner *et al.*, 2007; Yin *et al.*, 2011).

Groundwater budget components are nearly impossible to measure directly and they must be quantified by indirect methods. It is difficult to estimate groundwater recharge and discharge reliably by one method because of uncertainties and assumptions associated with different methods (Yin *et al.*, 2011). For this reason, it is commonly recommended that the water budget should be estimated using multiple methods to constrain recharge estimates (Healy and Cook, 2002; Scanlon *et al.*, 2002; Misstear *et al.*, 2009). In this study, the water table fluctuation (WTF) and the meteorological water budget (MWB) methods were used to estimate the groundwater budget in the Zamfara State water catchment (part of Sokoto-Rima basin, Nigeria).

The main objectives of this study are to present the application of different methods, to compare the results of groundwater budget and evaluate methods applied in part of Sokoto-Rima basin. In this paper, the water-table fluctuation (WTF) method and meteorological water budget (MWB) were used to estimate the groundwater budget.

2.0. Regional Hydrogeology of the Study Area

The study area is part of the Sokoto-Rima Hydrogeological Province of Nigeria, which is underlain largely by basement rock types (Figure 1). These include granites, gneisses, schists, phyllites and quartzites. Groundwater in the upland areas of crystalline rocks is generally available in small quantities from fractures or other tabular partings and from the weathered rock (regolith) just beneath the land surface. The fractures are usually most open above a depth of 100 m but, even so, yields to boreholes are relatively low with high drawdown. Normally, Basement aquifers are developed within either the regolith (relatively high storativity but low permeability) or the fractured bedrock (low storage capacity with a relatively high permeability) according to (Yaya *et al.,* 2001; Ogilbee and Anderson, 1973).

Nonetheless, towards the base of the weathered zone at the interface with the fresh bedrock, the permeability is usually high, allowing water to move freely due to the low proportion of clayey materials. However, in such situations, deep-seated fractures are an important source of groundwater and can sometimes provide appreciable water supplies, especially when tectonically controlled (Mac-Donald *et al.,* 2005).

The water table in crystalline rock is partly phreatic and partly piezometric. In the rock mass, the joint planes act as a water barrier. The water table is inclined and follows a general topography of the ground. The inflow of water comes from infiltrated rainfall, while outflow of water takes place in springs or rivers. The hydraulic pressure of water in a rock depends on the depth below the water surface, and works on the face at both sides of the joint with a tendency to open the joint.

However, about 20% of the study area is underlain by sedimentary rock series of Gundumi formation (Figure 2). These include streams and lacustrine deposit, with comparatively coarser materials than any of the younger overlying formations of the Sokoto Basins. In the north near Isa and Sabon Birni, discontinuous lenses of quartz and feldspar pebble gravel are interbedded with more abundant clay and clayey sand. Farther south along the Gusau-Sokoto road, sandy beds prevail over gravel. However, the formation still contains a great deal of intermixed clay. The sandy beds decrease and clay beds increase with depth and to east toward the contact with the Pre-Cretaceous basement rocks but, near the base of Gundumi, a conglomerate of rounded quartz pebble up to 11/2 inches in diameter occurs in outcrop (Ogilbee and Anderson, 1973; Offodile, 2002).
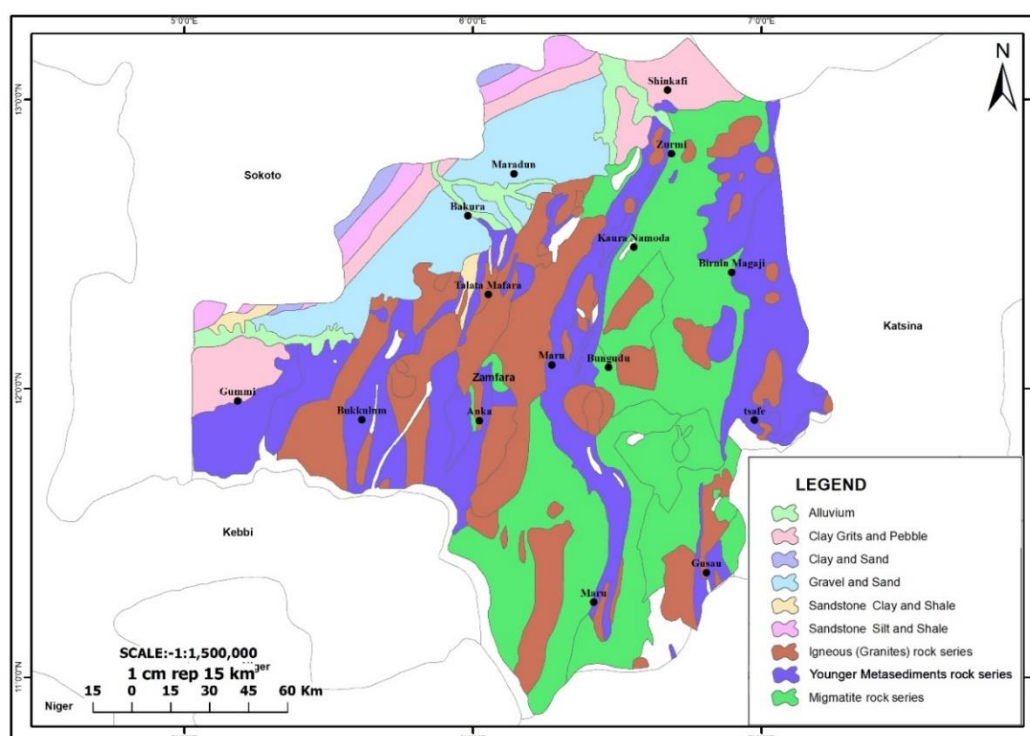
Figure 1: Simplified geological sketch of the study area

3.0. Methodology

A geological map of the study area was prepared with the help of ArcGIS 10.8 (Figure 1). Annual rainfall has been measured at three stations (Gusau, Bakura and Talata Mafara stations) by the State Meteorology Works. The rainfall map of the basin was prepared using measured annual rainfall data with Isohyetal method (Figure 2). Evapotranspiration was determined with the Thornthwaite method (Thornthwaite and Mather, 1957) as obtained from the satellite. The streamflow was measured at the streamflow gauging station which is located in Sokoto river manage by National Water Resource Institute, this compensate for the satellite data (Figure 4). For this study, groundwater head measurements were made in two hundred and eighty (280) wells during the peak of dry season 2018 and the peak of dry season 2018 (one hydrologic year) in both sedimentary and fractured aquifers. Absolute altitudes were measured by means of a differential global positioning system (GPS). The hydraulic conductivity and transmissibility coefficients of the aquifers were determined using well pumping test results from those boreholes using Aquifer Test 4.0 Pro-software with Cooper–Jacob method. This involves the collection of pumping test data and subsequent calculations of different hydrogeological parameters. Water level measurements were used to determine the groundwater budget with the WTF method. Additional data including climatic, and well production data were used in this study to calculate the water budget of the Zamfara water catchment with the MWB method.
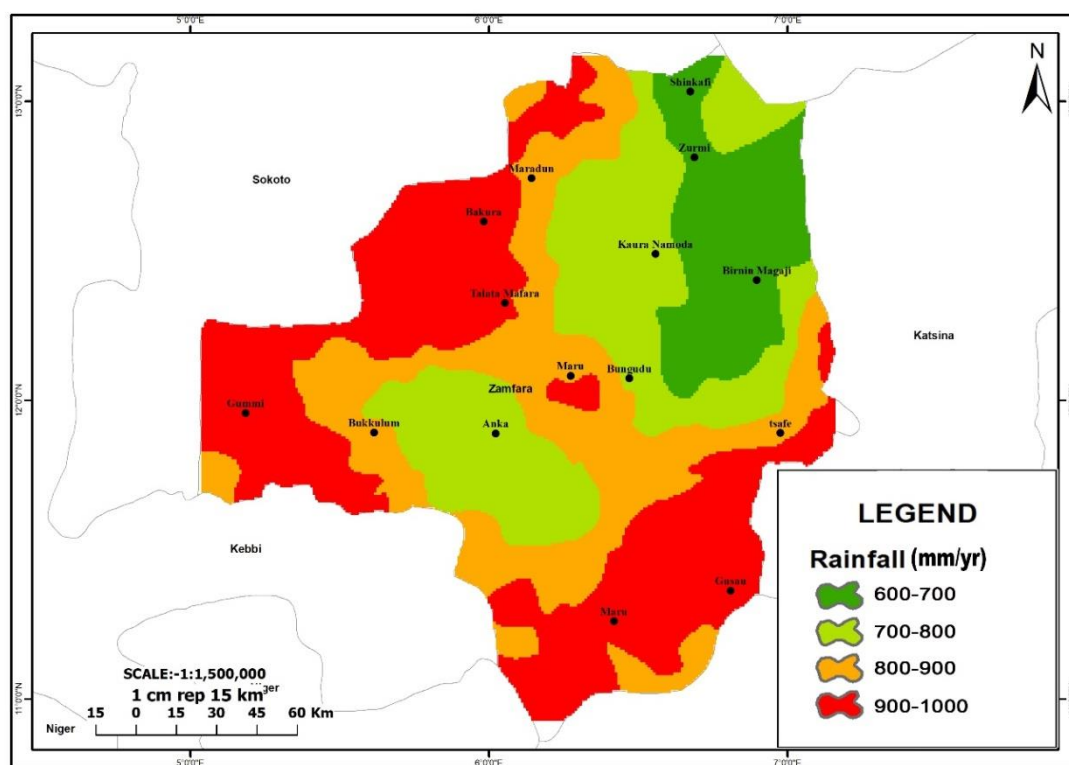
**Figure 2:** Isohyet map of the study area

3.1. Water budget concept

The water budget is an accounting of the inflow to, outflow from, and storage within a hydraulic unit such as a basin or aquifer. This concept requires that a balance must exist between the total quantity of water entering and the total quantity of water going out in the water catchment. Under natural conditions and over long periods of time (before any development), groundwater recharge is balanced by groundwater discharge, that is, Recharge = Discharge. As groundwater is nearly always moving, it will naturally flow from the recharge areas to the discharge areas. The discharge from the aquifers may occur in a variety of ways such as flow to streams, lakes, springs, water use (Sophocleous, 2005).

An idealized conceptual groundwater model was developed for the study area (Figure 3). The surface flow (runoff) moves towards the western direction. Much of the rainfall evapotranspirated or flow on the surface as runoff and the remaining percent infiltrate into the ground to recharge the aquifers

(Figure 3). The topographical/geological framework favors the western part of the study area which is underlain by sedimentary formation. Where fracture exists within the basement terrain slope becomes a barrier for water infiltration. It is worthy to note that there is higher evapotranspiration at western part compared to the rest part of the area of study whereas the reverse is the case for the runoff potential (Figure 3).
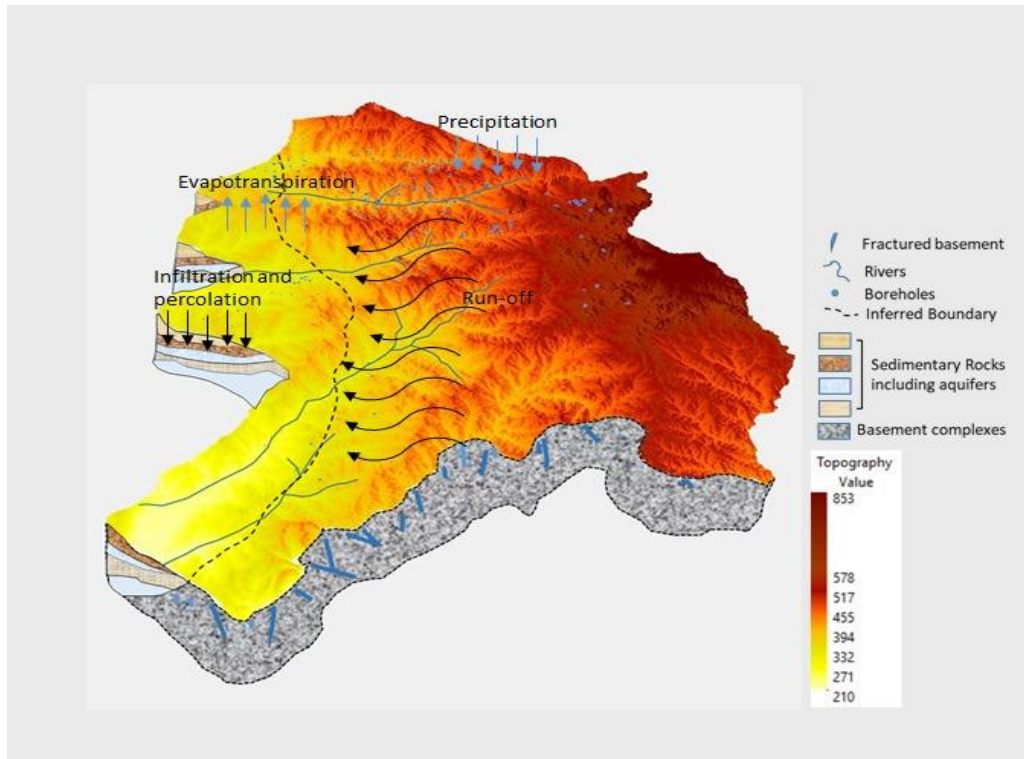
Figure 3: Groundwater conceptual model

3.2. Meteorological Water Budget Method (MWB)

The simple meteorological water budget method (MWB) has been widely used for quantifying groundwater recharge (Equation 1). The MWB method is an integral component of any conceptual model of the system under study. The MWB method is a water balance equation. It is related to the inputs and outputs of a hydrologic system mathematically according to the law of conservation of mass. The water balance equation is given by:

$$\sum Qin = \sum Qout \tag{1}$$

Q_{in}: sum of all inflows over a period of time (groundwater recharge) and Q_{out}: sum of all outflows over a period of time (groundwater discharge).

3.3. Groundwater recharge

There are two recharge sources of the aquifer in the Zamfara water catchment. These are: Infiltration from direct rainfall and Infiltration from irrigation water.

Rainfall: The most important source of recharge is the infiltration from direct rainfall. The rate of recharge from direct rainfall depends on the amount and duration of precipitation in the Zamfara water catchment. The isohyet method (Linsley *et al.* 1975) was used to calculate the distribution of rainfall areas. Annual rainfall has been measured at three stations as earlier stated. The rainfall map of the area was prepared using measured annual rainfall data with the isohyetal method (Figure 2). The mean rainfall is calculated using the following formula in Equation (2).

$$P = \sum [A_n (P_n + P_n + 1)/2] \sum A_n \tag{2}$$

where P_n are the isohyet values and A_n are the areas between isohyets. The mean rainfall was calculated using this method. Recharge from average annual precipitation was calculated.

3.3.1. Infiltration from irrigation water

Irrigation water for agricultural activities has been supplied majorly from surface water, Bakolori dam in the entire Zamfara water catchment. Irrigation from dam are provided via canals. Not all the irrigation water reaches the root zone of the plants. Part of the water is lost during its transport through the channels and in the fields. The remaining part is stored in the root zone and eventually used by the plants. In other words, only part of the water is used efficiently, the rest of the water is lost for the crops on the fields that were to be irrigated.

Based on the discharge data available from the major dam (bakolori dam) within the study area, about 12.21 million m^3 of water is released from the dam annually. In this case, 60% of irrigation water from the dam and ponds is used by vegetation and the remainder 40% of water infiltrated into the ground is evaporated, thus it is assumed that only 15% of water released from the dam get infiltrated.

3.3.2. Groundwater discharge

Evapotranspiration: The most important discharge component of groundwater in the study area is evapotranspiration. According to the meteorological data, the highest temperature in the study area occurs in March (when it reaches 40^{0}C), while the lowest value is in December (when it reaches 26.5∘C). The Thornthwaite method (Thornthwaite and Mather, 1957) is one of the most reliable and applicable, among the available water-budget methods (Scozzafava and Tallini, 2001; Panagopoulos *et al.,* 2002; Voudouris, 2006). The Thornthwaite method is used to evaluate potential and actual evapotranspiration. The potential evapotranspiration (Ep in mm) is defined as the maximum obtainable value of evapotranspiration in wet-soil conditions. The potential evapotranspiration (Ep) is calculated using Equation (3,4, and 5):

$$Ep(mm) = 16(10t/I)a \times p \tag{3}$$

Where t is the monthly temperature (∘C) and I is the annual heat index.

$$I = I \tag{4}$$

Where I is the monthly heat index   I = (t/5)1.514 (5)

The evapotranspiration data was entirely retrieved from the satellite and standardized with average evapotranspiration from *in situ* source data obtained from the management of Bakolori dam along with its coordinates which were geospatially analysed as presented in Figure 4.
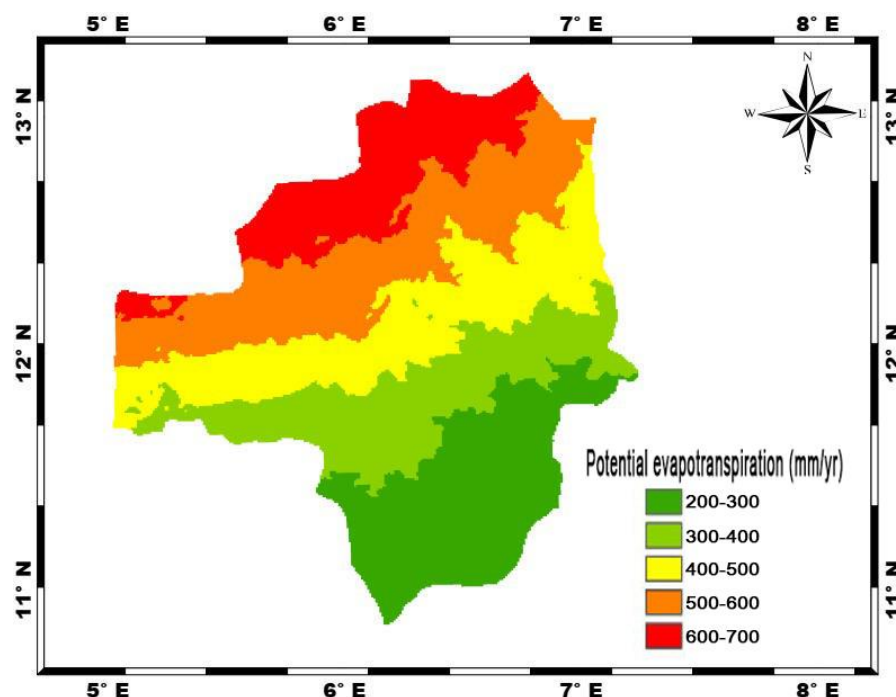
Figure 4: Potential evapotranspiration of the study area

3.3.3. Groundwater abstraction from wells

The average yield of wells which are drilled on the Gundumi Formation is 116.8 m^3/day and 49.1 m^3/day for the wells sited within the basement rocks. To determine groundwater abstraction amount from wells in the study area. The total abstraction of groundwater is estimated to be based on 5 working hours per day and 365 days per year of wells using Equation (6).

$$Q_{ga} \ (m^3/year) = Q_{wy} \times Th \times Td \tag{6}$$

Where Q_{wy} is the average yield of a well (m^3/day), (Th) is hours worked per day of a well (s), Td is days worked per year of a well.

3.3.4. Surface run-off

The surface flow (runoff) moves towards the western part of the study area which is enhanced by slope and the geological framework. Runoff potential was obtained from the satellite data and standardize with the field data obtained from JICA (2014) report. The data obtained were geospatially analyzed using ArcGIS 10.8 as shown in Figure 5.
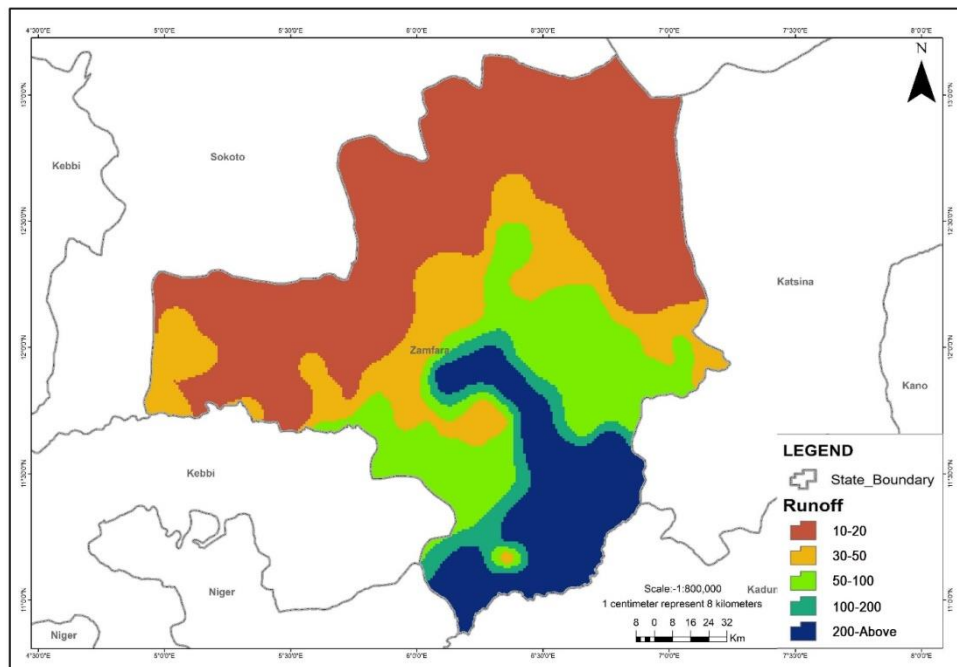
Figure 5: Runoff potential of the study area

3.3.5. Groundwater balance

The groundwater balance equation of the study area is given by Equation (7):

$$Rr + R_i + = Et + Q_{ga} + Q_{sur} \tag{7}$$

Where R_r is the recharge from rainfall, R_i is the infiltration from irrigation water (dam), E_t is the Evapotranspiration, Q_{ga} is the total abstraction from wells, and Q_{sur} is the surface run-off. The meteorological groundwater budget of the study area is summarized in Table 1.

3.4. Water Table Fluctuation Method (WTF)

The water level fluctuates primarily in response to variation in recharge and discharge rates. The fluctuations are reflected by the water level changes in wells in response to the changes in groundwater storage. The groundwater table starts to rise during June to September period due to an increase in infiltration from precipitation. Water table fluctuation (WTF) method evaluates changes in groundwater.

The WTF method presented by Healy and Cook (2002) is the most widely used method. This method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. In other words, volume change of groundwater in an aquifer is

calculated from the groundwater level changes. Difficulties in applying the method are related to determining specific yield and groundwater level decrease (Scanlon *et al.,* 2002; Moon *et al.,* 2004; Crosbie *et al.,* 2005; Jie *et al.,* 2011). Other limitations of the WTF method are given as regionalizing results may significantly reduce the accuracy of the calculated recharge because groundwater level fluctuations measured in a well are only representative for a small area of a heterogeneous aquifer and WTF methods can only be used for shallow, unconfined aquifers (Healy and Cook, 2002; Jie *et al.,* 2011). In the WTF method, recharge (R) calculates a given time interval (Δt) as the potential groundwater rise (Δh) multiplied by the specific yield (Sy) in Equation (8) (Healy and Cook, 2002). In this research rainfall in form of precipitation is considered as the major source of groundwater recharge, as such only five months of active rainfall in the study area is considered as the active time of recharge.

$$R = (Sy \times \Delta h)/\Delta t \tag{8}$$

Specific yield is in fact a function of media porosity, depth of the water table, drainage duration and the rest. The parameter is difficult to measure, and there is no efficient or widely accepted method for deriving it from other data (Jie *et al.,* 2011). Effective porosity is often equated to the specific yield of the porous material or assumed that the volume of water in the pore space can be freely drained by gravity due to the change in the hydraulic head (Kresic and Stevanovic, 2009). The effective porosity and specific yield is accepted as equal in most practical field applications (Kasenow, 2001). A detailed description of each step which is performed in this study is presented below:

Step 1: Groundwater levels were measured in March 2018–September 2018, at one period and matches according to the static conditions in the geographic basin. The groundwater level is between 0.43 and 25.7 m in the basin.

Step 2: According to the variation of groundwater level, groundwater level fluctuation maps for 2018 period was prepared (figures 4). These map are divided into zones which have iso-level exchange. These zones were classified as I zone (< 5 m), II zone (5 - 10 m), III zone (15 – 20 m), IV zone (20 – 25m) and V zone (< 25m). The areas of each zone on these maps were calculated.
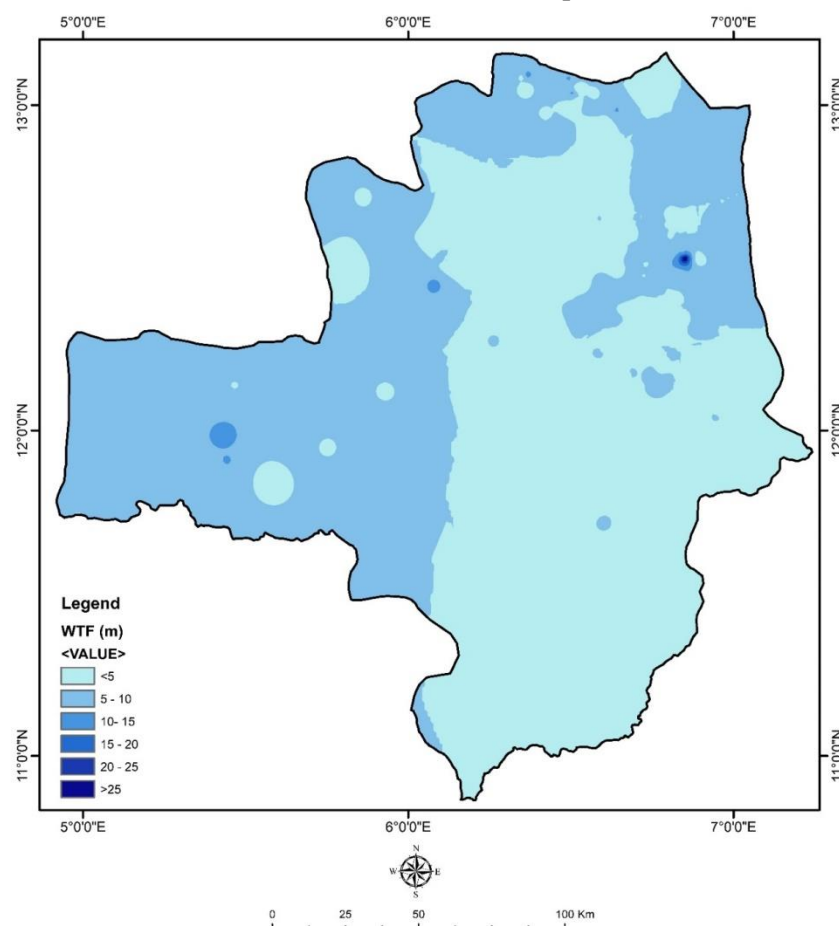
Figure 6: Groundwater fluctuation map of the study area

Step 3: In this study, reserve (R) was estimated using groundwater rise and effective porosity values considering WTF method approach using equation (9). Unlike WTF method, R was calculated using the formula of volume change which was presented by Castany (1963).

$$R = A \times \Delta h \times ne \tag{9}$$

Where A is the area of each zone, Δh is the groundwater rise and (ne) is the effective porosity of each zone.

Step 4: The effective porosity (ne) was determined using hydraulic conductivity (k) values of aquifer with equation (10) developed by Marotz (1968).

$$ne = 0.462 + 0.045 \ln k. \tag{10}$$

The values of hydraulic conductivity (k) were calculated with Cooper–Jacob time method using Aquifer Test 3.5 software from pumping tests results of 280 wells in the study area.

Step 5: The groundwater recharges (reserve) for each zone were calculated using equation (9) and these results were given in Table 5.

4.0. Results and Discussion

The result of the meteorological water budget method (using Equation 7) of the study area is summarized in Table 1. The hydrologic budget goes towards the positive trend (111,693,470 m³/year), when the input values reach (176,129,081 m³/year) which is greater than the output which was calculated as (64,435,611 m³/year) (Table 1). The contribution of evapotranspiration to the total discharge rate is approximately 40% and the contribution of rainfall to the total recharge rate is also approximately 95% in this budget. 78,185,429 m³/year which is equal to 70% of the differences between total recharge and discharge was estimated as annual reserve storage in the entire Zamfara water catchment area, considering the probable errors made in calculations and measurements.

Table 1: Groundwater balance between the input and output quantities

Recharge	(x 10⁶) m³/year	Discharge	(x 10⁶) m³/year
Rainfall	172,949,330	Evapotranspiration	25,942,399
Infiltration from Irrigation	3,179,751	Runoff	17,294,933
Total	176,129,081	Abstraction from Wells	21,198,339
Difference:	111,693,470	Total	64,435,611

According to the calculation based on water table fluctuation (WTF) as presented in Table 2. Total groundwater reserve was calculated as 111,342,057.3m³/year. The difference between the two methods (that is MWB and WTF) is 351,413 m³/year which accounts for approximately 0.3% of the total water reserve from both methods.

Table 2: Groundwater reserve base on Water Table Fluctuation (WTF)

Range of fluctuation	Area	Effective Porosity	Ground water level change	Hydraulic conductivity	Ground water Reserve
<5	23678500	0.655	2.79	0.602052459	43271274.83
5 to 10	15963507	0.028	6.5	0.160813953	67964631.05
10 to 15	108908	0.028	12.6	0.509	38422.7424
15 to 20	72000	0.028	15.96	0.3242	32175.36
21 to 25	35080	0.028	22	0.1419	21609.28
>25	16600	0.028	30	0.1242	13944
Total					**111,342,057.3**

Recharge Rate versus Aquifer Abstraction: the result of aquifer recharge using Equation (8) is presented in Table 3. The statistical summary of 245 borehole wells tapping basement complex rock units revealed a recharge rate that rage between 45.88 to 1396.22 m³/year with mean value of 235.65. However, the calculation of abstraction from those wells using Equation (6) revealed results that range between 29675 to 473040m³/year with an average value of 89519.7 (Table 4).

Table 3: Statistical summary of recharge/abstraction within basement rock units

| Parameter	N	Minimum	Maximum	Sum	Mean	Std. Deviation
Recharge	245	45.88	1396.22	138410	235.65	198.77
Abstraction	245	29674.5	473040	14,591,715	89519.72	71170.49
SWL	245	2.51	30.6	824.45	5.06	3.13
Yield	245	16.26	259.2	7995.46	49.05	38.99

The result of the recharge rate within the sedimentary formation is presented in Table 4. The minimum and maximum recharge are between 93.57 to 2253.31 m^3/year with mean value of 747.83 against the abstraction from the aquifer which ranges between 34493 to 630720m^3/year.

The spatial distribution of groundwater recharge pattern in the study area (Figure 7) shows that western part which is underlain by sedimentary formation received more quantity of water flow (surface and groundwater flows).

Table 4: Statistical summary of recharge/abstraction within sedimentary formation

Parameter	N	Minimum	Maximum	Sum	Mean	Std. Deviation
Recharge	35	93.57	2253.31	26174	747.83	511
Abstraction	35	34492.5	630720	6349606	181417.3	127398.89
SWL	35	1.9	19.6	269.31	7.69	3.67
Yield	35	18.9	345.6	3479.24	99.41	69.81

This suggests that the groundwater reserve of the study area is very meagre, as an abstraction from the aquifers are higher than the recharge rate as revealed from table 3 and 4. Thus prudent measure have to be adopted for adequate water use per head as population increases and demographic change will exacerbate more stress on the availability of these precious resources aside from the climate change impact. The implication is that further proliferation of borehole wells will deplete the entire aquifer and subject it to be devoid of manageable storage capacity, particularly in the crystalline aquiferous unit.
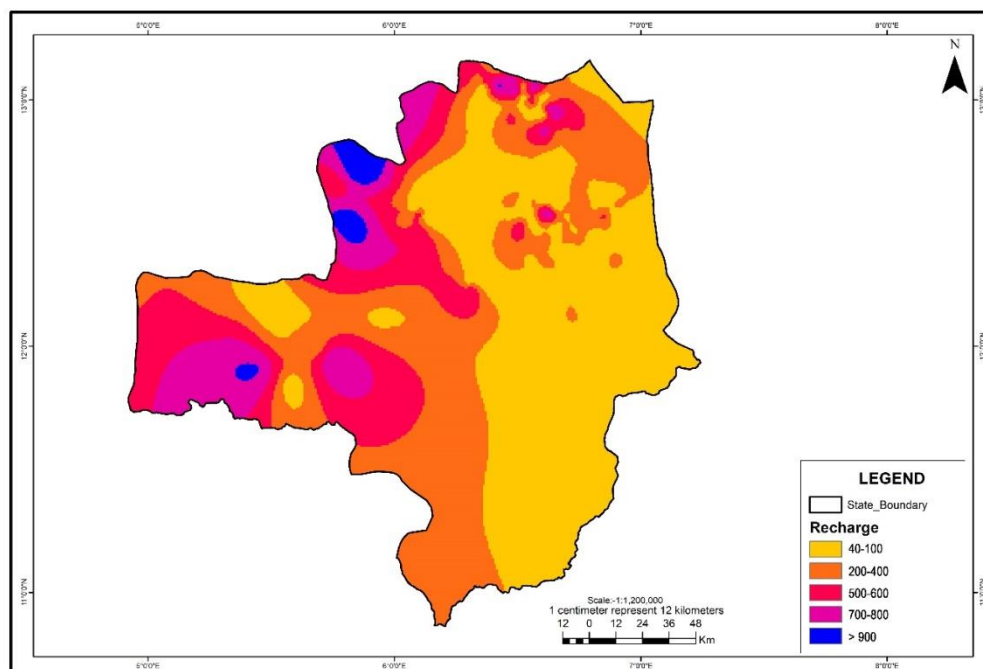
Figure: 7: Groundwater Recharge Across the Study Area

4.1. Groundwater Budget Base on the Geological Framework (GBBGF)

The map of study area (Figure 1) which was obtained from the Nigeria Geological Survey Agency, form the base information on the heterogeneity of the study area. For calculation of the groundwater reserve, pumping test results from borehole data were used to discern the aquifer pattern of various lithological units of the study area. The average thickness of the soft overburden/weathered layer on Pan-Africa Granite is 20 m, undifferentiated basement complex rocks (essentially granite-gneiss,

schist) is 25m, and on meta-sediments is 25m, and sedimentary series is 80m while the average depth to the groundwater table of granite is 8.6 mbgl, Older metasediments rock units is 8.8 mbgl, and on Younger meta-sediments is 9.9 mbgl, and sedimentary series is 12.5 mbgl respectively. Whereas; the average effective voidity of the soft overburden aquifer was calculated as 0.028, it is worthy to note that below soft overburden aquifer, there is a fractured crystalline aquifer. The thickness of the fractured crystalline aquifer, irrespective of the petrology of underlying rocks, for the purpose of this calculation has been assumed as 15 metres while its effective voidity is taken as 0.00145 using Equation (10).

The empirical model used by Al-Sefry *et al.* (2006) to calculate groundwater storage was used in this research as it has proven very successful in the estimation of groundwater resources of an area. Given by:

$$G_{Rs} = A*h*n \qquad (11)$$

Where A is the unsaturation surface area, h is the possible recharge layer depth, and n is the effective porosity. Equation (11) can be re-written as:

Groundwater Reserve Storage (G_{Rs}) = Saturated tshickness (average thickness of the Overburden/weathered layer – average depth to the water table) $\times$ Effective porosity $\times$ Area.

Two different aquiferous units were considered in the basement terrain. From Figure 1, a surface area underlain by different litho-stratigraphic units were calculated as follows:
1. Clay grits and pebble + Sandstone/Mudstone = 4925350 m^2 + 4299280 m^2 = 9,224,630 m^2.
2. Pan-Africa Older Granites = 7470512 m^2.
3. Undifferentiated Meta-sediment = 8328033 m^2.
4. Undifferentiated Basement Complex (Granite-gneiss, Schist, minor Migmatized rock units) = 14571645 m^2.

4.1.1. Groundwater storage capacity of the older metasediments (metamorphic) rock units
Hence the total groundwater water storage (sGWRt) for the aquifer of the soft overburden unit within undifferentiated basement complex rock units = 14571645 m^2 $\times$ Saturated thickness (25 m – 8.8 m) $\times$ effective porosity (0.028) =   6,609,698.2 m^3.

The groundwater storage capacity for the fracture aquifer units = Area (14571645) m^2 $\times$ effective porosity (0.00145) $\times$ average fracture thickness (15 m) = 3, 169, 33.2 m^3.

Since there are two types of aquifer units within this rock formation the total groundwater storage will be given as the total sum of static groundwater resources within the overburden unit (6609698.2 m^3) + fracture aquifer unit (316933.2 m^3) = 6,926,631.4 m^3.

4.1.2. Groundwater storage capacity of the younger meta-sediment rock unit
Following from the aforementioned analysis the total groundwater storage capacity (sGWRt) for the aquifer of the soft overburden unit within this rock unit = Area (8328033 m^2) $\times$ Saturated thickness (25 m – 9.9 m) $\times$ effective porosity (0.028) = 3,521,092 m^3.

The groundwater storage capacity for the fracture aquifer units = Area (8328033 m^2) $\times$ effective porosity (0.00145) $\times$ average fracture thickness (15 m) = 181,135 m^3.

Since there are two type of aquifer units within this rock formation the total groundwater storage will be given as the total sum of static groundwater resources within overburden unit (3521092 m^3) + fracture aquifer unit (181135 m^3) = 3,702,227 m^3.

Total Groundwater Reserve within Metamorphic rock units = 6,926,631.4 + 3,702,227 = 10,628,858.4 m^3

4.1.3. Groundwater storage capacity for the pan-Africa (older) granites

Following from the aforementioned analysis the total groundwater storage capacity (sGWRt) for the aquifer of the soft overburden unit within this rock unit = Area (7470512 m^2) × Saturated thickness (20 m – 8.6 m) × effective porosity (0.028) =   2,405,505 m^3.

The groundwater storage capacity for the fracture aquifer units = Area (7470512 m^2) × effective porosity (0.00145) × average fracture thickness (15 m) = 162,484 m^3.

Since there are two type of aquifer units within this rock formation the total groundwater storage capacity will be given as the total sum of static groundwater resources within overburden unit (2,405,505 m^3) + fracture aquifer unit (162,484 m^3) =   2,567,989 m^3.

4.1.4. Groundwater storage capacity the clay grits/pebble and sandstone/mudstone (gundumi sedimentary formation)

The total groundwater water storage (GWRt) for the aquifer of the sedimentary unit within this rock unit = Area (9,224,630 m^2) × Saturated thickness (80m – 12.5m) × effective porosity (0.655) = 33,854,392 m^3.

The water budget base on the geological framework of the study area as shown in table 6 revealed 80% of the groundwater storage capacity within the sedimentary formation which underlain approximately 20% of the entire study area, whereas, the basement complex hosts the remaining 20% of the groundwater storage which underlain 80% of the study area (Table 6).

The implication is that two third of the population of the domestic users reside within the area underlain by basement complex rock units.

Table 6: Groundwater storage of Zamfara State base geological framework

Hydrogeological Province	Lithology	Area		Saturated Thickness (metre)	Effective Voidity	Total Static Fresh Groundwater resources, Million Cubic Metres
Sedimentary Hydrogeological Province	Sandstone Gundumi Formation	9,224,630	20%	80m (Aquifer thickness) – 12.5 mbgl (Static well level)	0.655	62,266,253
Crystalline Hydrogeological Province	Granites, Rhyolite & Other Volcanics	7,470,512	22%	20m (Overburden thickness) – 8.6mgl (Static well level)	0.028	2,567,989
Metamorphic rocks	Older/Younger metasediments rock units	22,899,678	57%	25m (Overburden thickness) – 8.8mgl (Static well level)	0.028	10,628,858.4
Total		39,594,820	100%		-	75,463,099

5.0. Conclusions

Three different methods were used to evaluate the groundwater storage capacity of Zamfara water catchment, part of Sokoto-Rima Basin. These methods have different approaches. The average groundwater budget of the study area was calculated as 111,693,470 m^3/year with the MWB method and it was calculated as 111,342,057.3 m^3/year and 73,463,099 m^3/year with the WTF and GBBGF methods respectively. The groundwater abstraction for domestic/agricultural uses was calculated to be higher than that of the recharge rate. It is shown that, if conceptual hydrogeological modelling of the basin is well known and reliable data are obtained, the MWB method gives accurate results in the

basins. However, comparison of multiple methods is valuable for determining the plausible budget amount and for highlighting the uncertainty of the estimate.

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